ANALYTIC CRITERIA FOR FUSES FOR EXPLOSIVE FLUX COMPRESSION GENERATORS

JAMES H. DEGNAN
High Energy Plasma Division
Phillips Laboratory
Kirtland Air Force Base, New Mexico

An approach to optimizing the fuse opening switch geometry for explosive magnetic flux compression generators (EMG's or MCG's) is analagous to that developed by Maisonnier, Linhart, and Gourlan[1] for inductive store/opening switch pulse sharpening of capacitor discharges. That is, the cross section of the fuses, should be related to the fuse material properties and the discharge current by the relation

$$s^2 = A/(\gamma \int \rho\, de) \tag{1}$$

where A = current action = $\int I^2 dt$

γ = fuse material density

ρ = fuse resistivity = $\rho(e)$

e = specific energy of fuse

The integration limits are from the start of the discharge to onset of vaporization (e=2.8 megajoules/kilogram for aluminum). For aluminum, $\gamma \int (1/\rho) de = 4.9 \times 10^{16}$ (MKS). Maisonnier modifies this criterion (equation 1) with a non-adiabatic parameter $K_1 = 2$.

$$s^2 = A/(K_1 \gamma \int \rho\, de) \tag{2}$$

Empirically, he found that $K_1 \approx 2$ fits fuse optimization data for capacitor discharges in the tens of kilojoule, several microsecond rise time range. The optimum length is chosen so that the energy to be dissipated in the fuse is just equal to the vaporization energy of the fuse (10.6 megajoules/kilogram for aluminum). We have found that such criteria are approximately correct for capacitor discharges up to the 20 megamp, several megajoule, few microsecond rise time range[2,3].

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The current action integral for a current waveform rising exponentially in time is conveniently simple:

$$A = \int_0^{t_m} (I_0 e^{t/\tau})^2 dt = I_0^2 \int e^{2t/\tau} dt \tag{3}$$

$$= \frac{1}{2} I_0^2 \tau (e^{2t/\tau} - 1)$$

$$= \frac{1}{2} I_0^2 \tau \left(\left(\frac{I_m}{I_o}\right)^2 - 1 \right)$$

$$\approx \frac{1}{2} I_m^2 \tau \ for\ I_m > I_o$$

EMG's of the helical or spiral type (helical stator outer conductors, central armatures, end-initiated) with varying pitch (continuously decreasing number of helical turns per unit length in the explosive propagation direction) can have such exponential current waveforms. Numerical modeling of such EMG's with realistic resistances, such that the current growth parameter α in

$$I = I_0 \ (L_0/L)^\alpha \tag{4}$$

is approximately 0.85 to 0.9 (where $L_0/L = 55$) indicates that the numerically calculated action is in the range 0.4 to 0.6 times the non-resistive analytic action, and the effective current growth time τ is approximately 1.2 to 1.3 times the non-resistive analytic τ.

Examples of numerical modeling of the performance of a fuse sharpened exponential EMG are shown below. The circuit is two loops, with the first loop including an EMG inductance $L_g = L_{go} e^{-t/\tau}$, a series resistance R_s, a series inductance L_s, a fuse resistance R_f, a fuse inductance L_f. The fuse effective resistivity is a piecewise continuous fit to $\rho(e)$, where $e = (\int I_f R_f \, dt)/m_f$, I_f is the fuse current, and m_f is the fuse mass. The second loop includes a closure switch (initially open, triggered by the fuse voltage exceeding a threshhold), a load resistance R_L, and load inductance L_L. The second loop is in parallel with the fuse. The loop currents are I_1, (EMG loop) and I_2 (the load loop). The fuse current is $I_f = I_1 - I_2 = I_1$ before the closure switch is triggered.

Before closure switch triggering

$$\frac{d}{dt}\,(I_1(L_g+L_s+L_f)) + I_1(R_s+R_f) = 0 \tag{5}$$

$$\frac{dI_1}{dt} = -I_1(\frac{dL_g}{dt}+R_s+R_f)/(L_g+L_s+L_f) \tag{6}$$

where $dL_g/dt = -L_g/\tau$, $R_f=\rho_f(x/s)$, ρ_f = fuse resistivity = function of $e=(\int I_f\, R_f\, dt)/m_f$, and the other elements are fixed.

After closure switch triggering

$$\frac{dI_1}{dt}(L_g+L_s+L_f) + I_1(\frac{dL_g}{dt}+R_s+R_f) - I_2R_f - \frac{dI_2}{dt}L_f = 0 \tag{7}$$

$$I_2R_L + \frac{dI_2}{dt}L_L + I_2R_f + \frac{dI_2}{dt}L_f - I_1R_f - \frac{dI_1}{dt}L_f = 0 \tag{8}$$

From (7) and (8) one readily obtains the iteration equations

$$\frac{dI_2}{dt} = [-I_2R_L - \frac{dI_1}{dt}(L_g+L_s) - \frac{dI_1}{dt}(L_g+R_s)]/L_L$$

$$\frac{dI_1}{dt} = [-\frac{dI_1}{dt}(\frac{dL_g}{dt}+R_s+R_f)+I_2R_f+\frac{dI_2}{dt}L_f]/(L_g+L_s+L_f)$$

Representative parameters, such as those used to obtain the plots below, are

L_{go} = 10 microhenry
τ = 10 microseconds
R_s = 4 milliohms
L_s = 0.0 ($L_{gf} = L_{go}e^{-4}$ = 0.182 microhenry)
I_o = 250 kiloamps
R_L = 1 milliohm
L_L = 0.182 microhenry

s = fuse area = 0.5 to 1.0 times simple analytic optimum
= 0.5 to 1.0 times 1.39 cm^2
x = fuse length = 1.19 to 1.7 meters

The fuse length is chosen so that the fuse mass has a vaporization energy of approximately half the peak predicted EMG magnetic energy.

The best performance predicted numerically is for fuse cross section 0.8 to 1 times the analytic optimum using non-adiabatic parameter K_1=2.

REFERENCES

1. C. Maisonnier et al, Rev.Sci.Instr. 37, 1380, 1966

2. R.E. Reinovsky et al, IEEE Trans.PlasmaSci. PS-10,73,1982

3. W.L. Baker et al, Megagauss III Proceedings, p.39, 1984

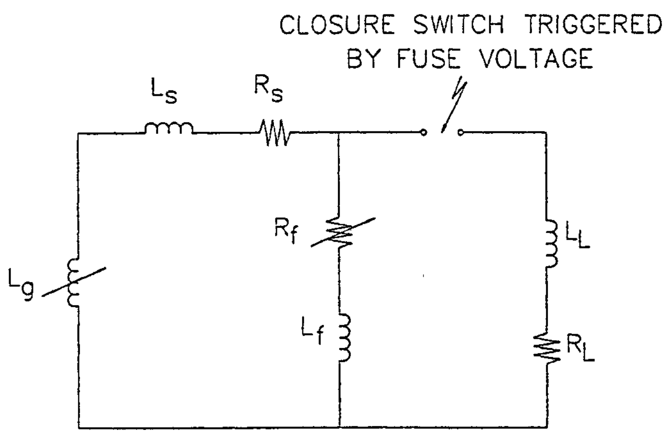
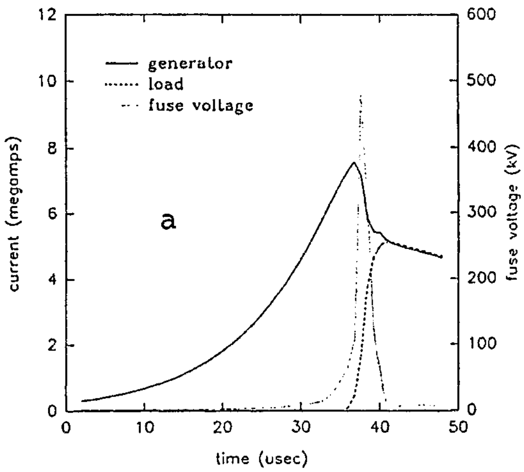
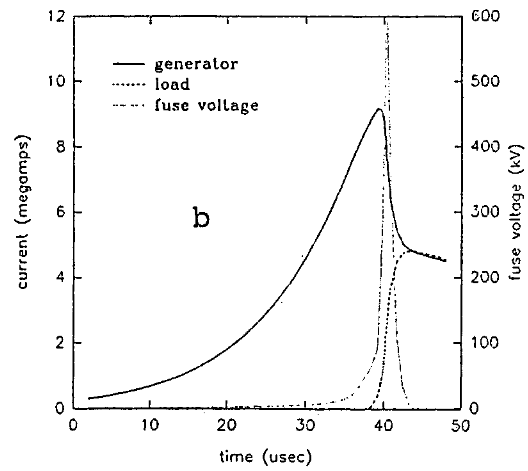
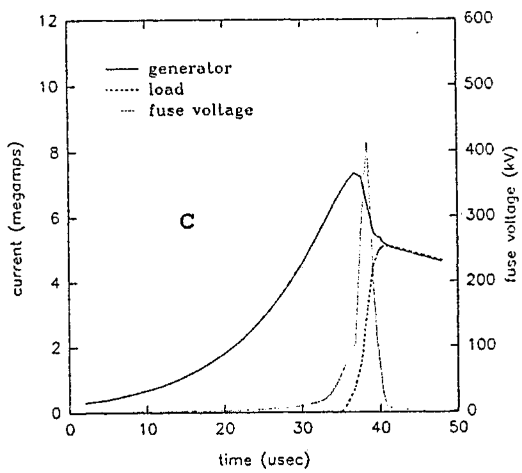
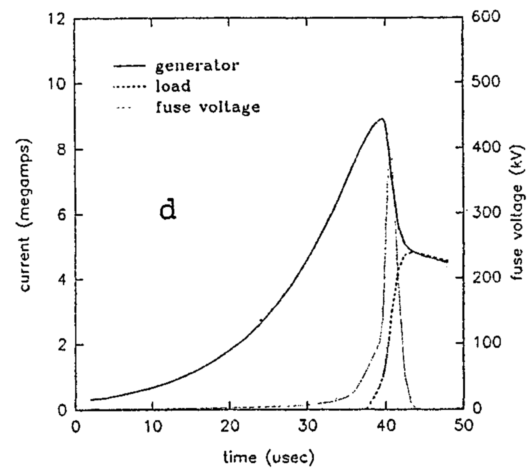


Figure 1. Explosive magnetic flux compression generator-fuse circuit. Elements are defined in text.









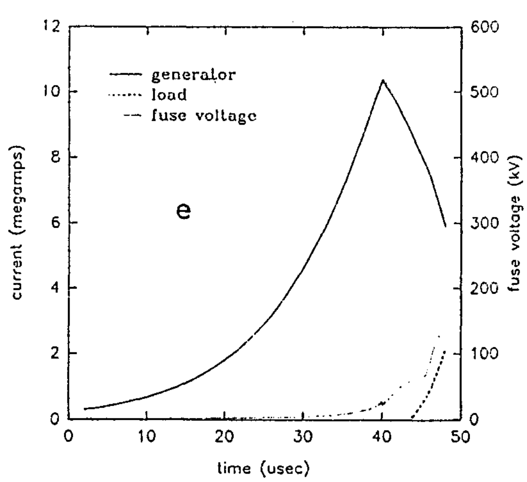


Figure 2. Generator current, load current, and fuse voltage vs time predicted by numerical modeling with circuit in Figure 1. Aluminum fuse length x (meters) and cross section s (cm squared) are (a) 1.19, 0.79, (b) 1.19, 0.98, (c) 1.705, 0.79, (d) 1.705, 0.98, (e) 1.705, 1.39